Impedance and Instabilities at the Advanced Photon Source

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Introduction

- Ring impedance of APS as-built did not agree with impedance budget (e.g. ID chamber impedance underestimated)
- Extensive computational and experimental study of impedance and single bunch, multibunch instabilities carried out
- Impedance database calculations agree with beam-based measurements (tune slope, response matrix)
- Tracking simulations including impedance agree with experimental results at ~70% level; discrepancies mostly understood
- Benchmarks increase our confidence that we can accurately predict effects of new chamber designs
- Rings with short bunches, many transitions e.g. small-gap IDs, etc, require more detailed calculations

APS[1] vs ILC Damping Ring Baseline[2]

	APS 24-bunch mode	APS 1296-bunch mode	APS 324-bunch mode	ILC DR
Energy (GeV)	7.0			5.0
Circumference (m)	1104			6695
Harmonic No.	1296			14516
Total current (mA)	100	100	100	402
Bunch charge (nC)	15	0.28	1.1	1.6 – 3.5
Bunch spacing (ns)	153	2.84	11.4	3.08
Bunch length (mm)	12	7.5	7.5	6.0
Avg β_x, β_y (m)	13.2, 16.1			13.1, 12.5
Emittance (nm)	2.5			0.515
Energy spread (%)	0.096			0.128
Momentum compaction	2.82e-4			4.2e-4
Synch tune	0.007			0.0958
Damping times, x,y/z (ms)	9.6/4.8			25.7/12.9

[1] http://www.aps.anl.gov/Facility/Storage_Ring_Parameters/

[2] "ILC Damping Rings OCS6 Lattice Parameters," Aug 21, 2006

Outline

- Impedance database results
- Modeling of machine studies
  - Vertical: TMCI
  - Longitudinal: microwave instability
  - Injection efficiency, accumulation limit
- Summary

Impedance Database I

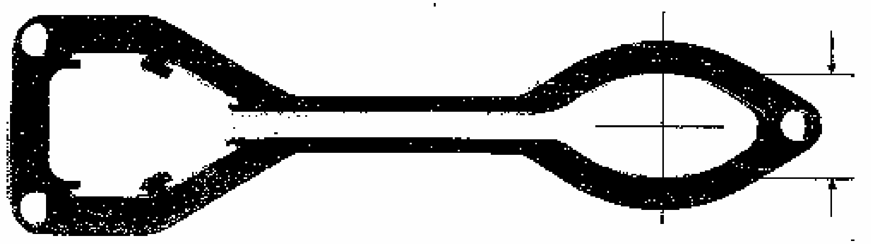
- **Impedance Database**
  - Wake potentials of 5-mm-long bunched beam
  - 3D Electromagnetic Field Solver MAFIA (serial program)
  - Impedance as function of frequency up to 20-30 GHz
  - OAG/APG Linux cluster (2 GB memory), during relatively low usage (ca. 2002)
  - Used to predict the collective effects in the APS storage ring

- **Conclusion: 70% Success**
  - Many of single bunch collective effects and current limits were explained qualitatively, and in some cases quantitatively
  - Calculated ID vacuum chamber impedance compared well with novel applications of beam-based methods (V. Sajaev, Proc. 2003 PAC, 417 and L. Emery, Proc. 2001 PAC, 1823)
  - Sufficient for machine studies, but not as operational tool in what-if simulations: details matter

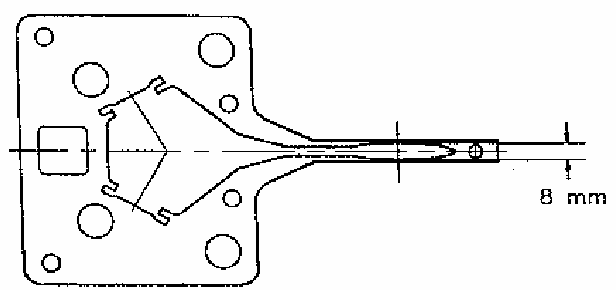
Mature operation demands realistic modeling of collective effects in testing various ideas: e.g. injection efficiency, single bunch limits & microwave instability, short x-ray generation

APS storage ring vacuum chamber

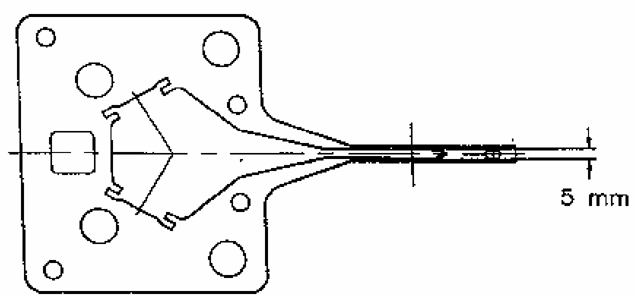
1104 m (incl. ~140 m ID chambers, ~64 m rf cavities)



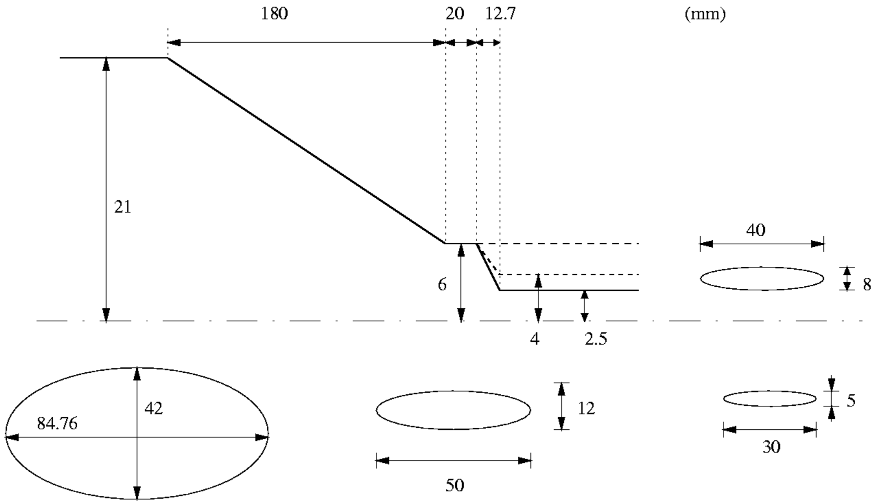
27 × 5 m long



1 × 5 m long



Undulator vacuum chamber transitions (5° slope overall; 15° at end):



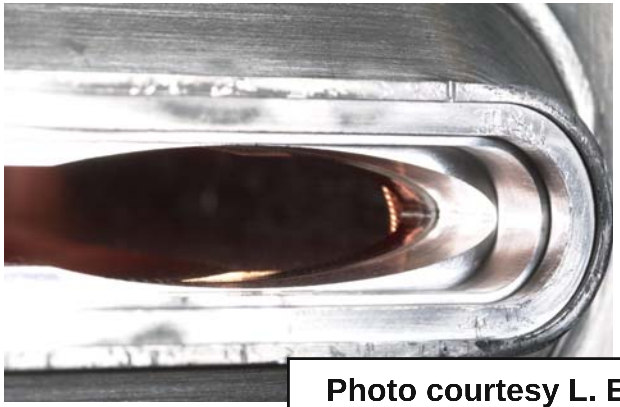
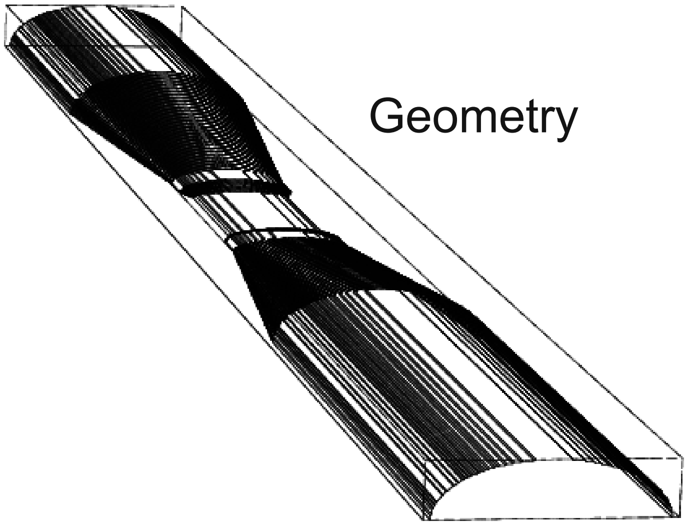
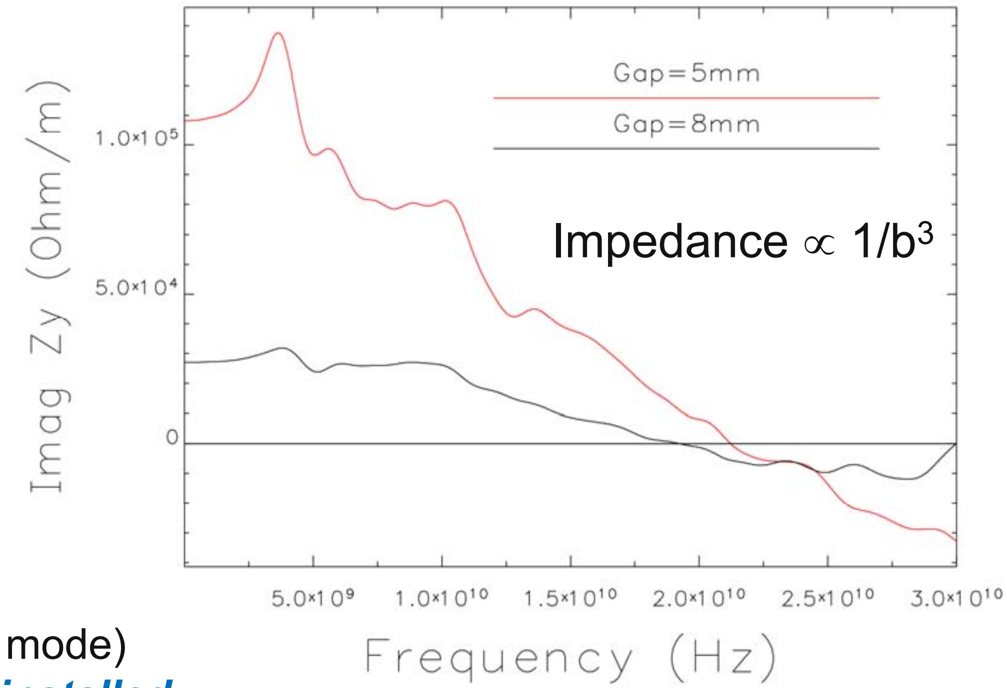


Photo courtesy L. Emery

ID chambers a major contribution to transverse impedance





Recent case (chromaticity of 24-bunch mode)

24 x 8-mm and 2 x 5-mm chambers installed

Zy = 1 MΩ/m

Mode coupling at 3 mA; stability limit at 5 mA

Worst case (same chromaticity)

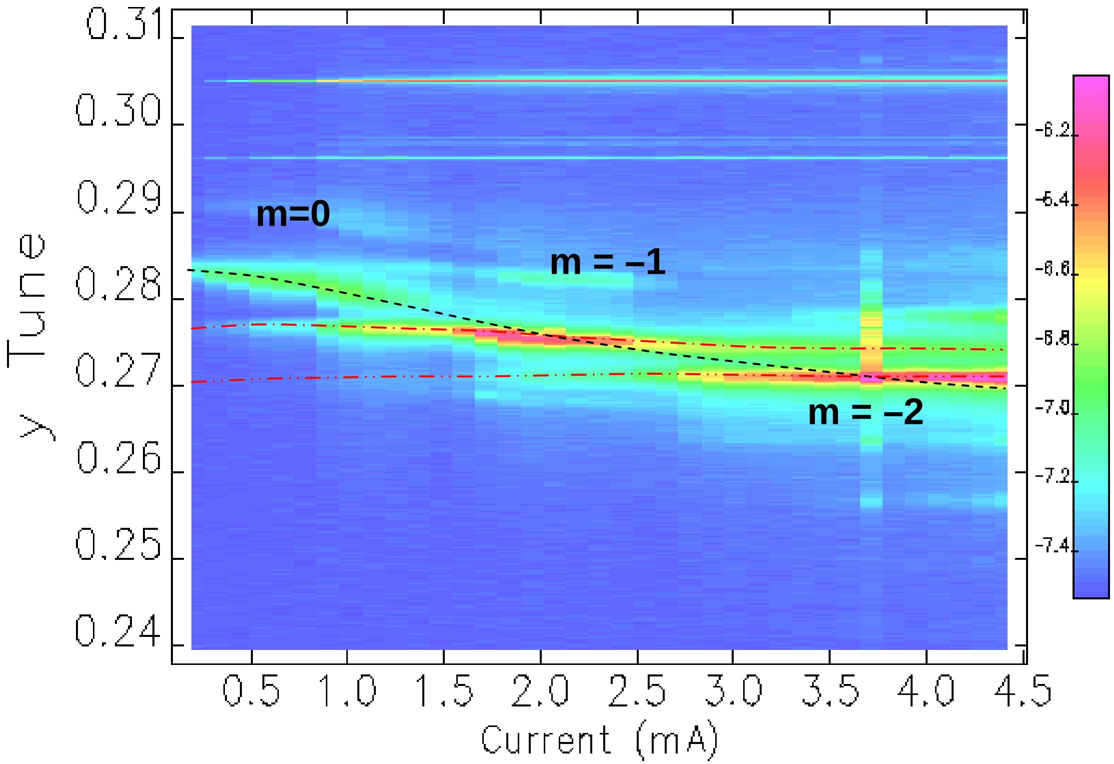
34 x 5-mm chambers installed in the ring

Zy = 3.5 M Ω/m

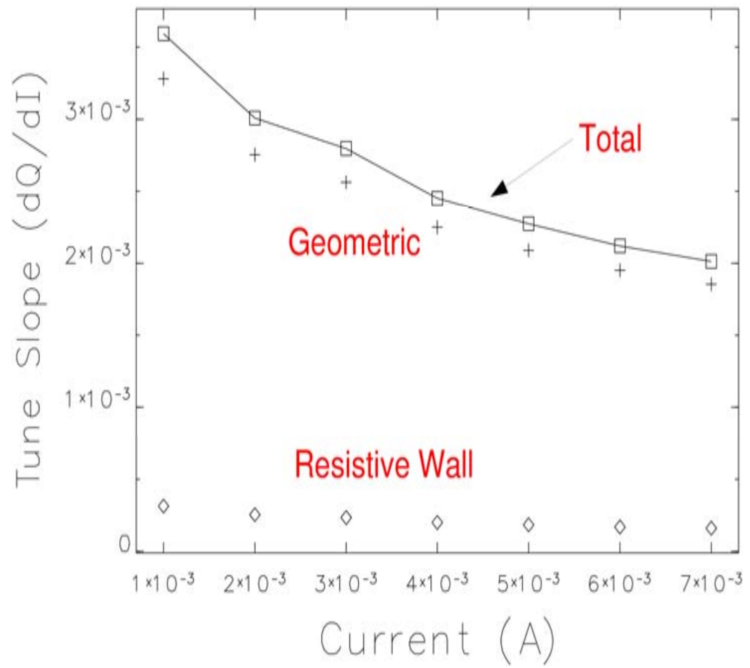
Mode coupling at ~1 mA; stability limit at ~1.5 mA

Slide courtesy Y.-C. Chae

Vertical tune with current: Geometric dominant



Measured tune slope (-0.026/mA)
[Data courtesy L. Emery]



Modeled with total vertical impedance in *elegant*[1]: (-0.022/mA) [Y.-C. Chae, Proc. PAC 2003, 3008]

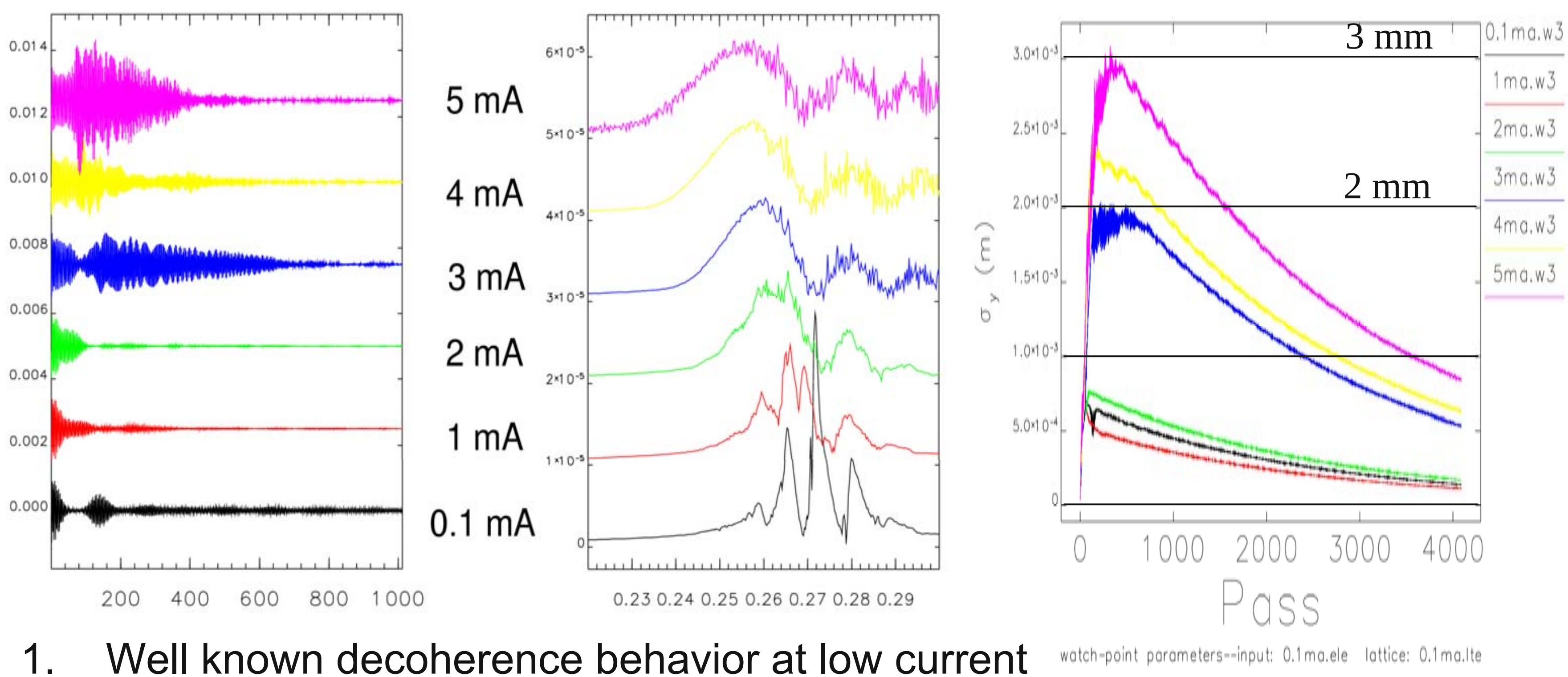
[1]M.Borland, “elegant: A flexible SDDS-compliant for accelerator simulation,” APS Light Source Note 287, 2000.

Vertical TMCI: Simulation

Slide courtesy Y.-C. Chae

7.5 nm lattice; chromaticity (4,4)

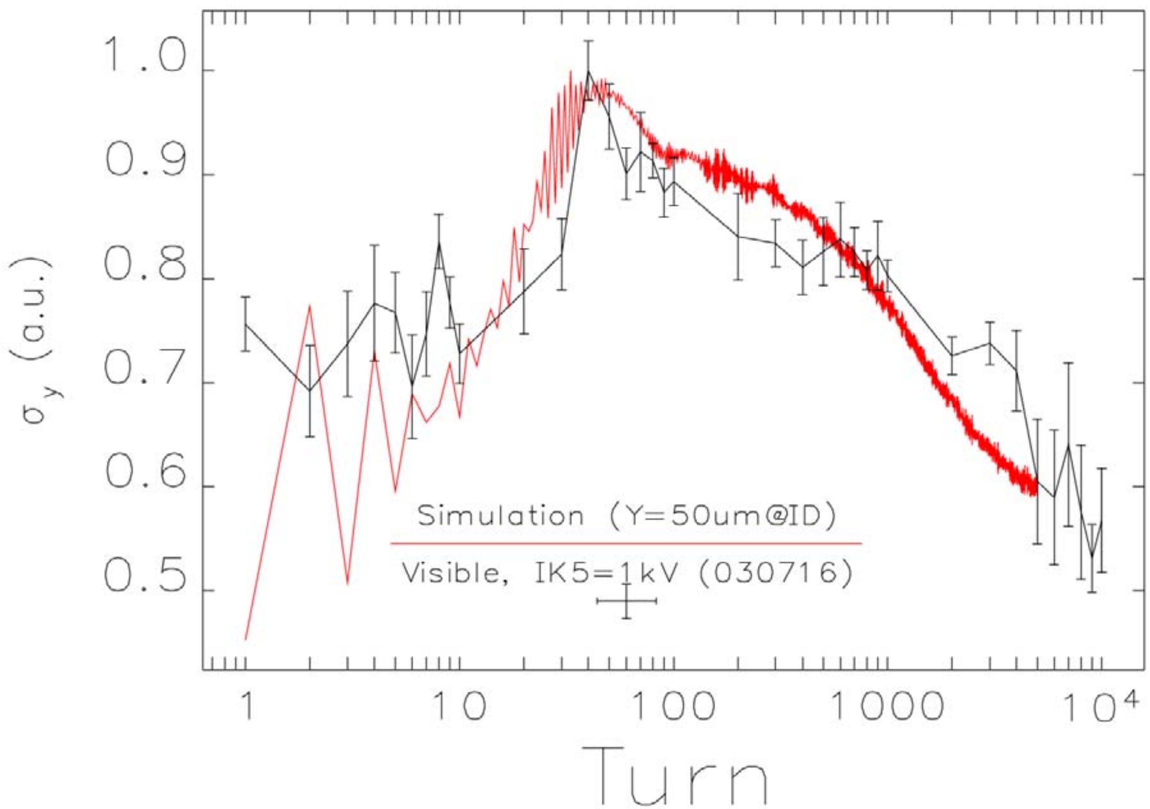
Centroid Kick Δy=1mm | Spectrum | Vertical Beam Size



1. Well known decoherence behavior at low current
2. Mode coupling completes 3 mA
3. Beam size blow-up above mode coupling ➔ Beam Loss due to 5-mm Insertion Device Chamber

Vertical Beam Size: Low Current (1 mA)

- Measurement: BM Visible, IK5=1 kV, 030716
- Simulation: ID, BBR-1, Δy=50 μm
- Beam size normalized by the maximum for comparison

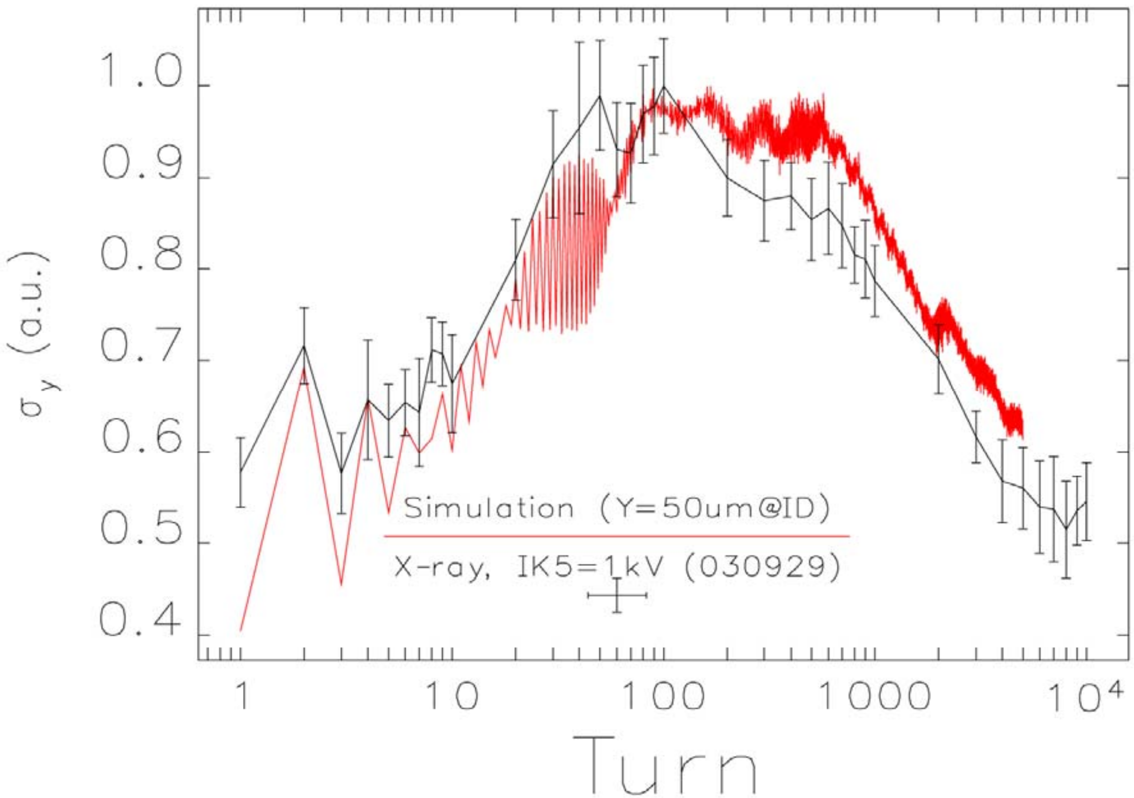


Good agreement!

Slide, data courtesy
Y.-C. Chae, B. Yang

Vertical Beam Size: High Current (5 mA)

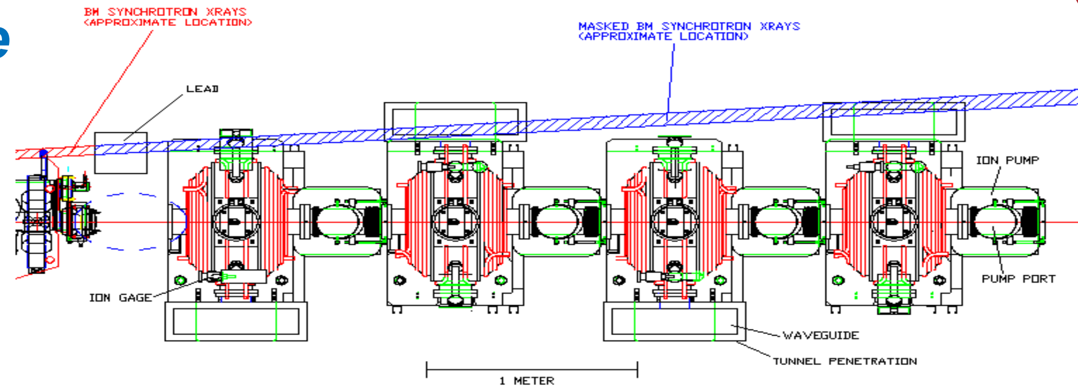
- Measurement: ID LN_2 cooled mono, IK5=1 kV, 030929
- Simulation: ID, BBR-1, Δy=50 μm
- Beam size normalized by the maximum for comparison

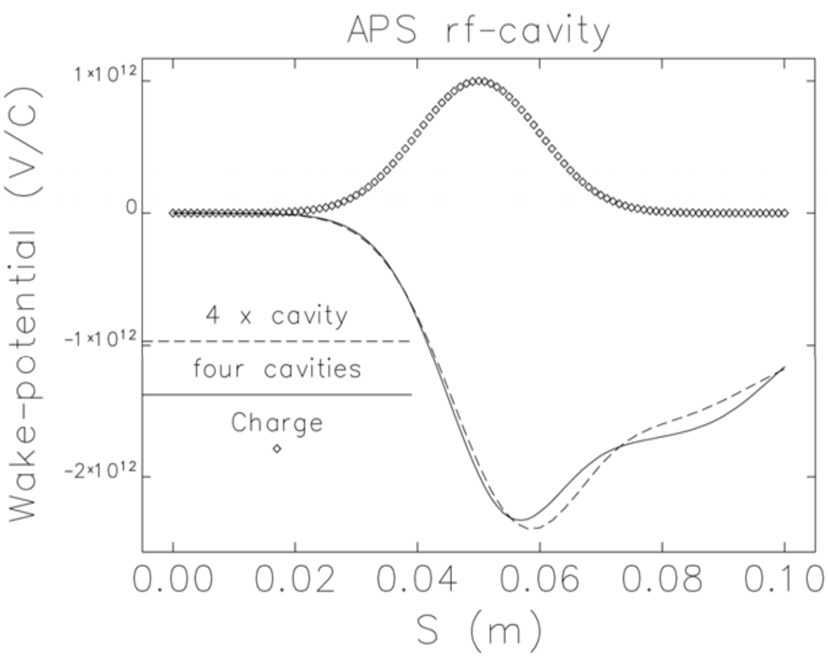


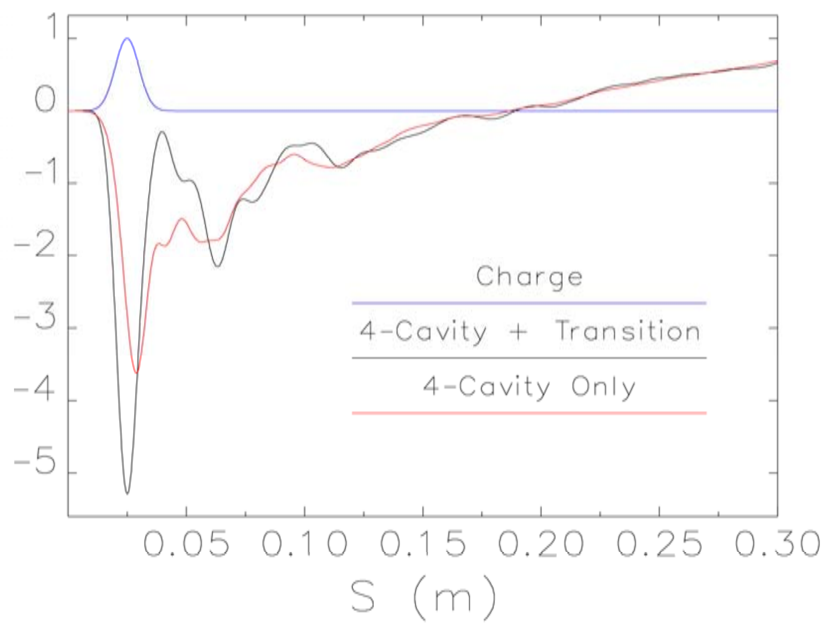
ID source provides better agreements with simulation!

Slide, data courtesy Y.-C. Chae, B. Yang

RF Cavity: Interference







4 x single cavity vs. 4-cavities in a row
➔ Interference small

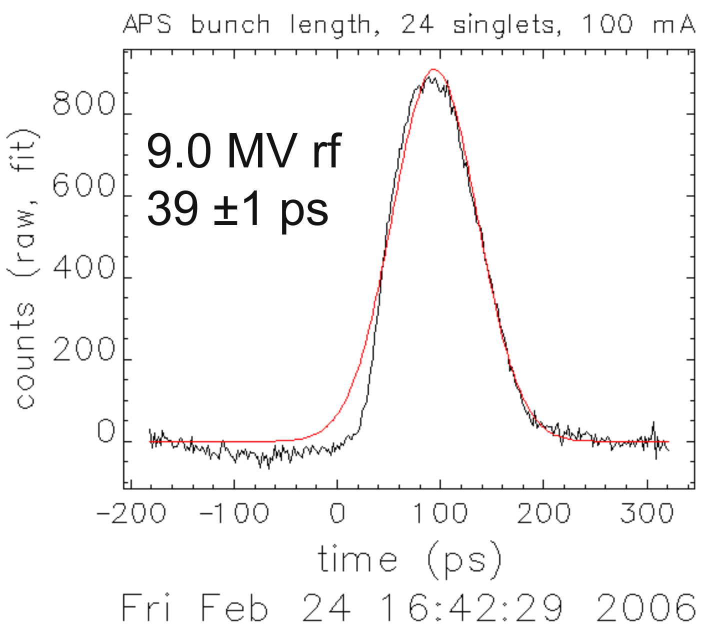
4-cavities in a row vs. ..+ transition
➔ Interference large

Slide courtesy Y.-C. Chae

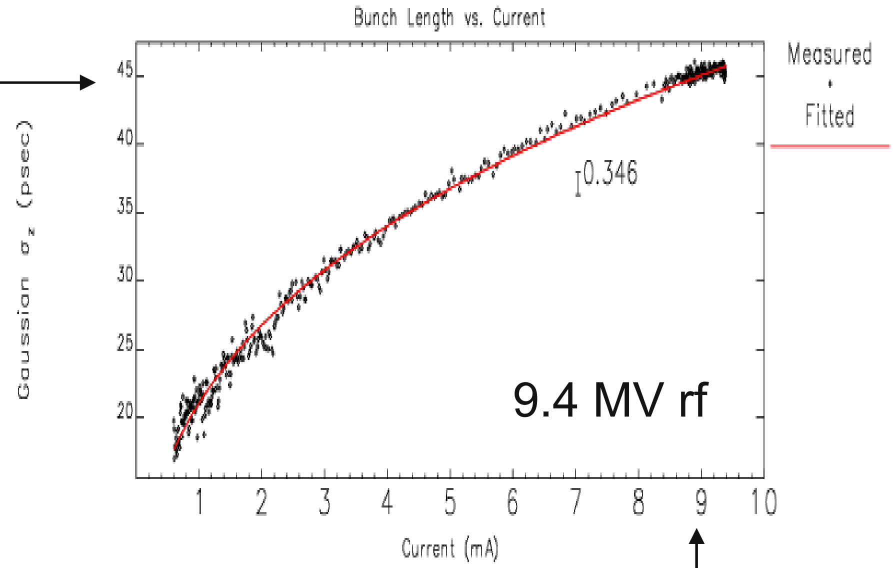
Bunch lengthening: potential well distortion

- Bunch length fit, calc Z/n: 0.5 Ω
- Comparison with model: 0.42 Ω

- Temporal profile: recent user request



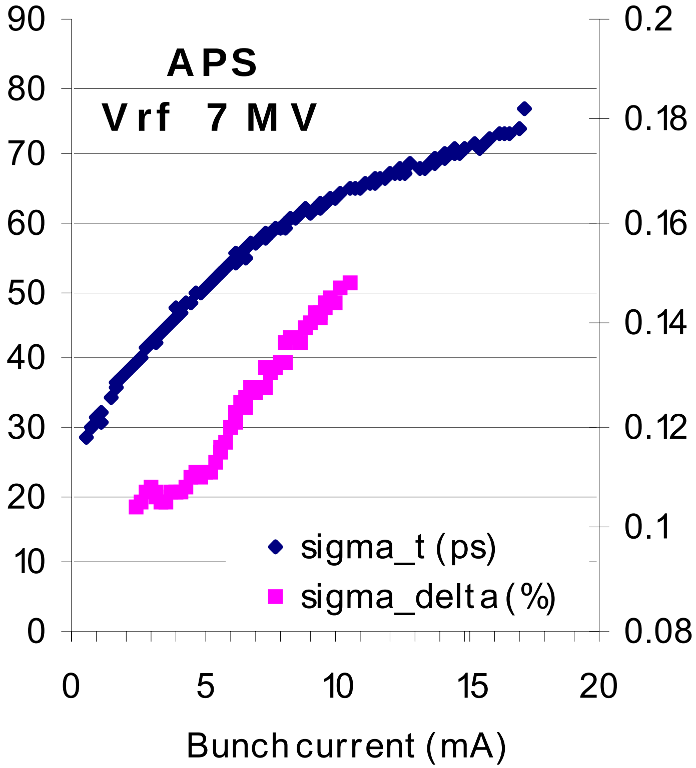
Measured during top-up: 4.25 mA/bunch



Y.Chae et al., Proc. 2001 PAC, 1817

Longitudinal microwave instability: Measurements

σ_E: BM and ID



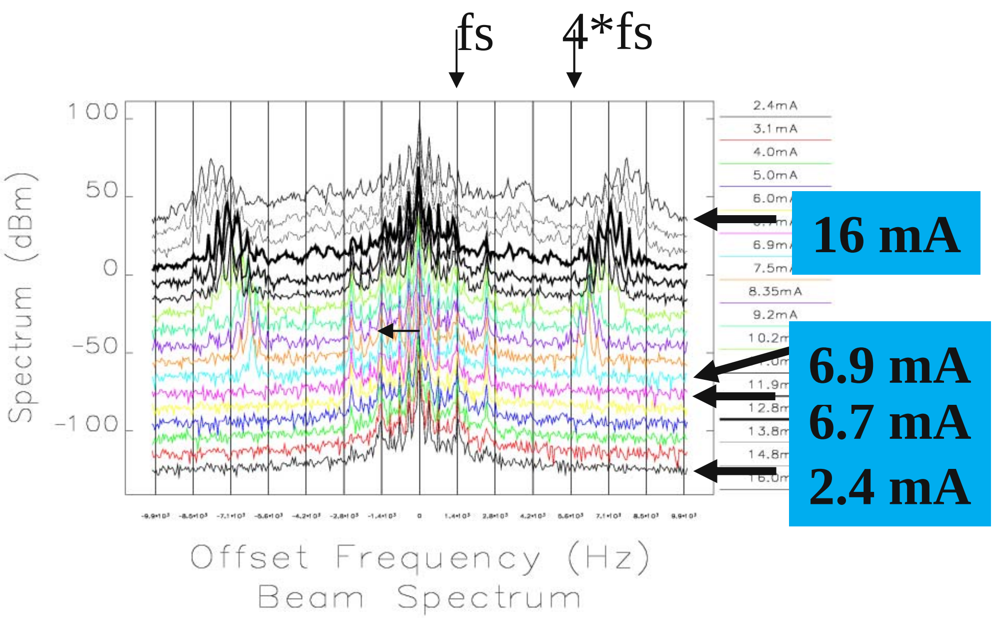


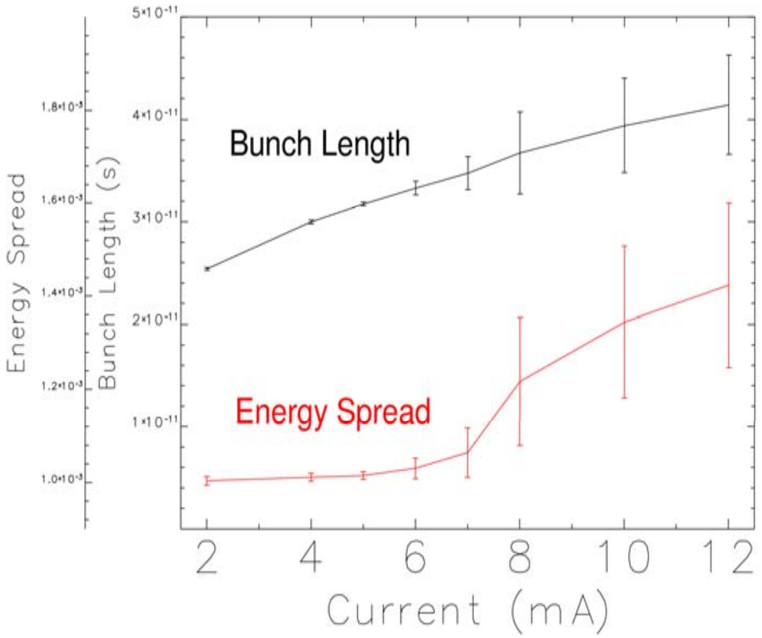
Fig. courtesy Y.-C. Chae

K.Harkay et al., Proc. 2002 EPAC, 1505; thanks to B.Yang

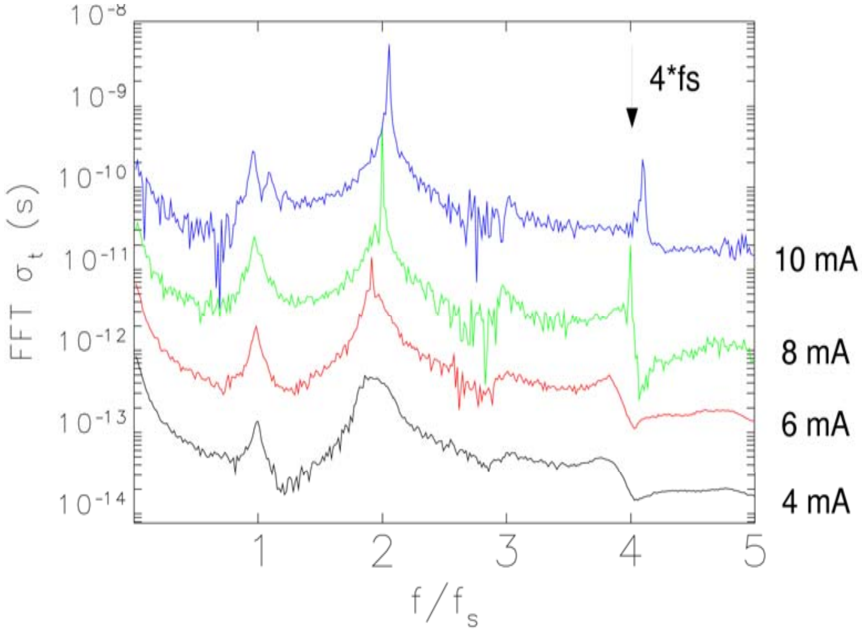
ESRF: 6 GeV, 10 nC (σ_z 40 ps); APS: 7 GeV, 18 nC (σ_z 50 ps); Spring-8: 8 GeV, 23 nC (σ_z 58 ps)

Longitudinal microwave instability: Simulation

- Energy spread blowup bunch current onset ~7 mA very well reproduced
- Magnitude of energy spread growth: scaling issues need to be resolved



Bunch Length/Energy Spread

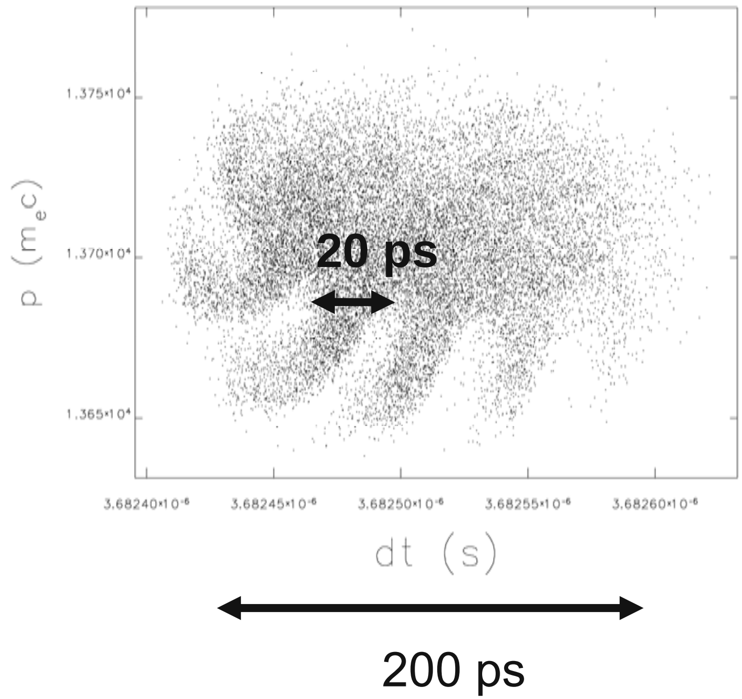


Bunch Length Oscillation

Slide courtesy Y.-C. Chae

Longitudinal microwave instability: Phase space

- Good agreement was obtained by impedance 80% larger than the calculated total impedance
- Sometimes we observe complex (energy-time) phase space evolution from the simulation (see plot at right)
- This result had never been verified at the APS (need to improve noise diagnostics issues), but SPring-8 believes this is a true phenomena
- Need short bunch wake potential in order to resolve density modulation of 20 ps and smaller



Slide courtesy Y.-C. Chae

Simulation of Injection Process

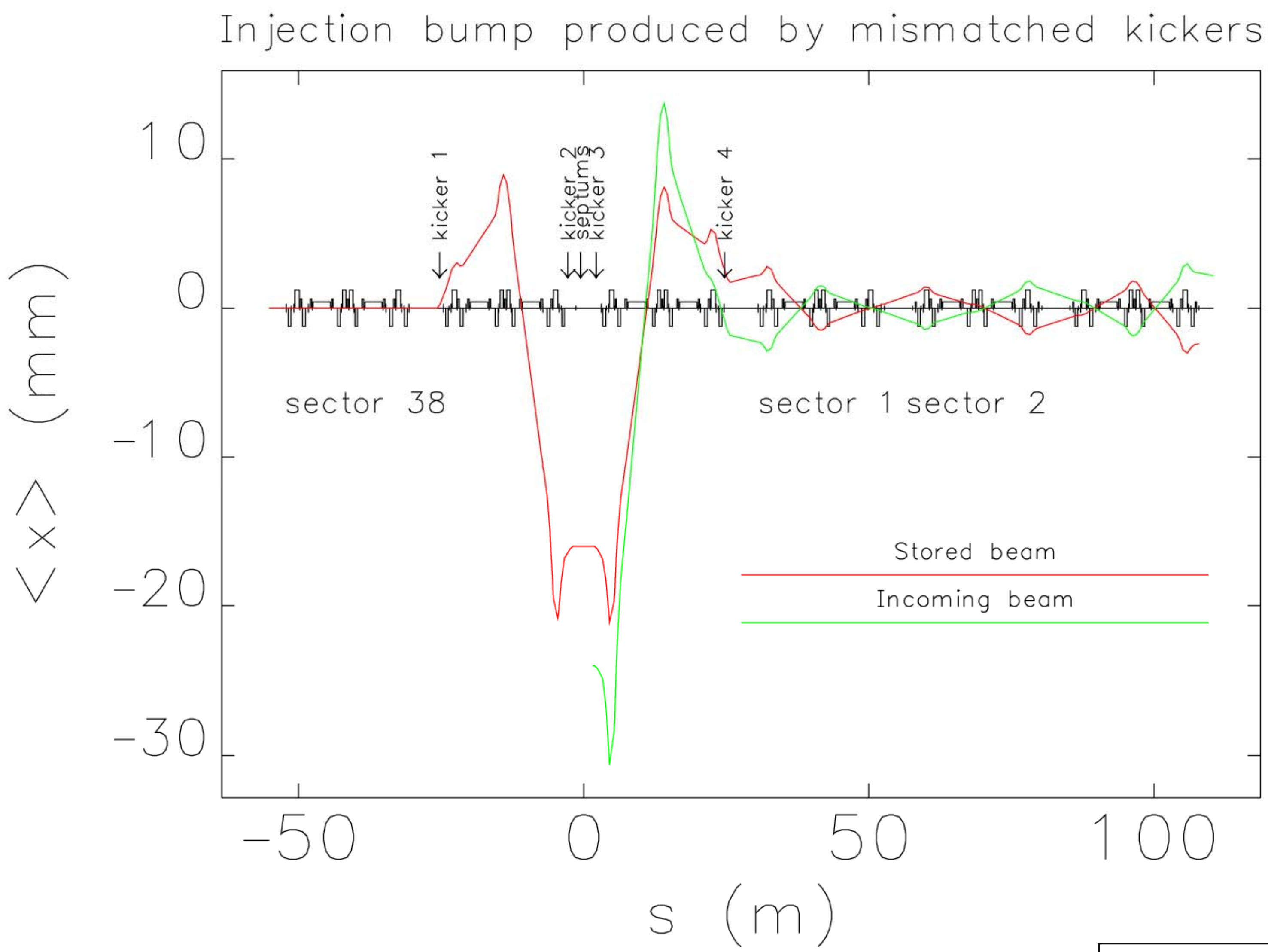
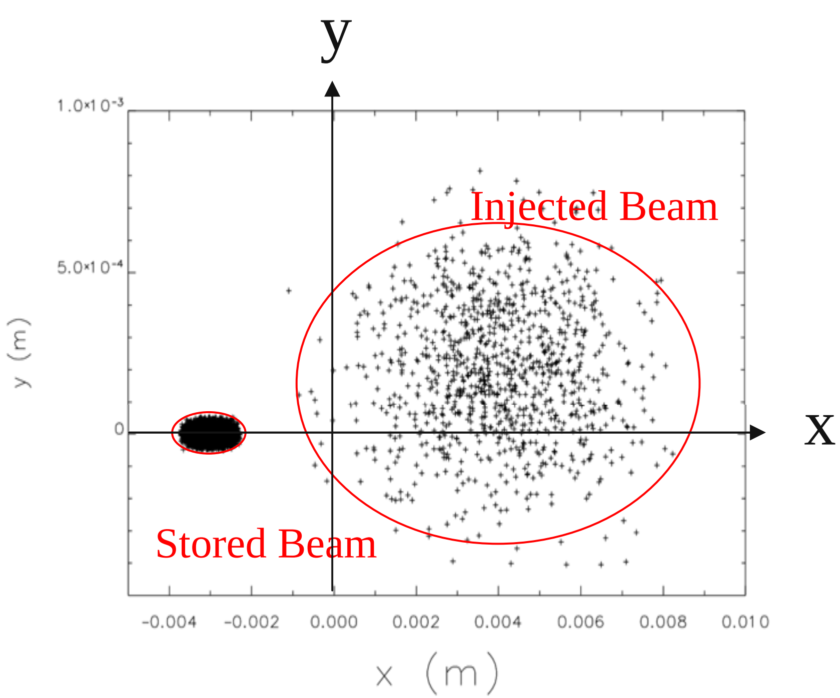


Fig. courtesy L. Emery

Initial Condition of Beam Simulating Injection Scheme



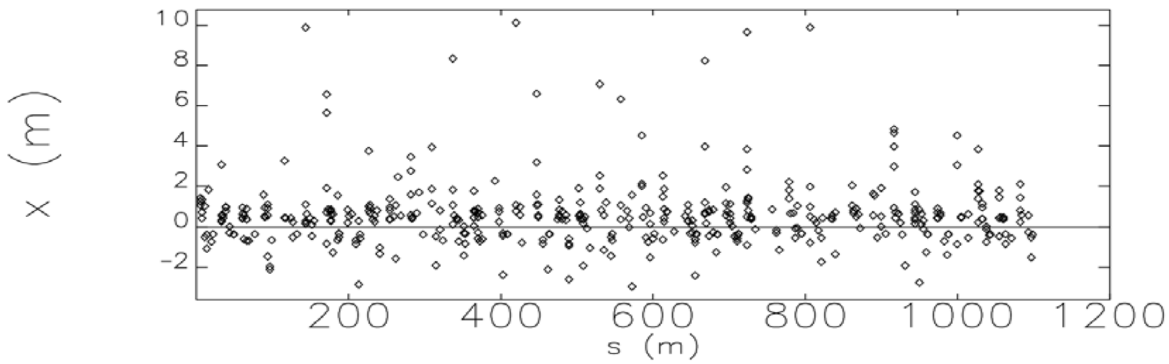
Coordinates of Initial Beam at the center of ID straight

	Stored beam	Injected beam
Δx (mm)	3	4
Δy (mm)	0	0.2
ε_x (m)	3e-9	1.5e-7
$\varepsilon_y/\varepsilon_x$ (%)	3	10
β_x (m)	20	20
β_y (m)	3	3
σ_s (mm)	7 - 12	24
σ_p (%)	0.1- 0.13	0.1

Slide courtesy Y.-C. Chae

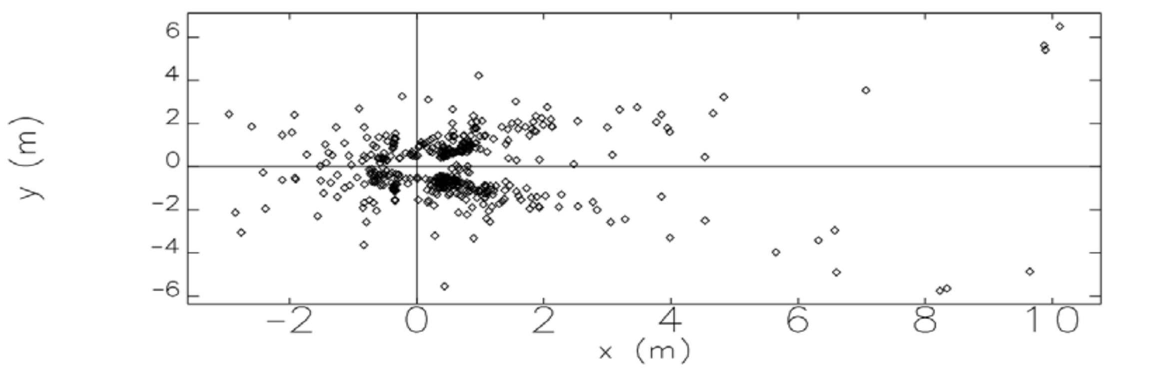
Particle Loss: Dynamic Aperture

x vs. s



Particle loss around ring

x vs. y

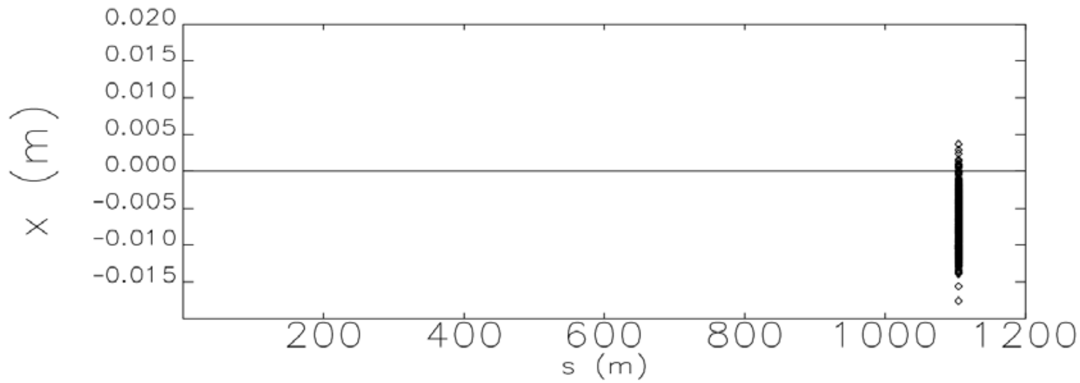


Coordinates of the lost particles

Slide courtesy Y.-C. Chae

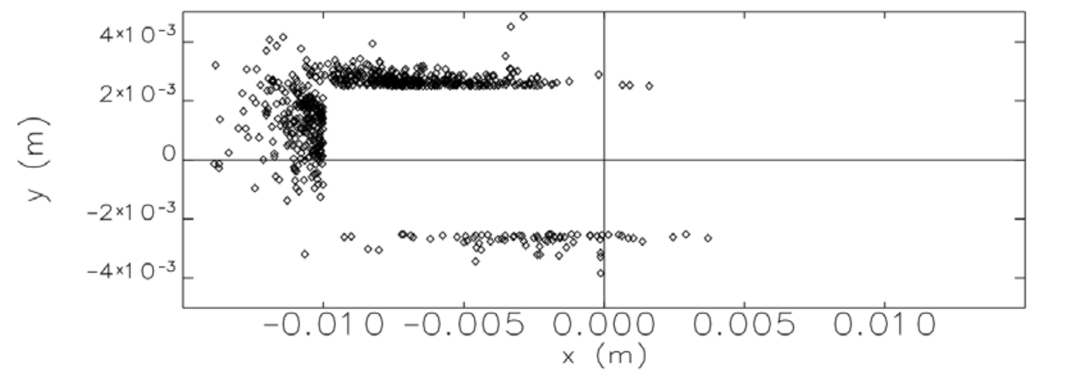
Particle Loss: Physical Aperture

x vs. s



Particle loss localized by aperture

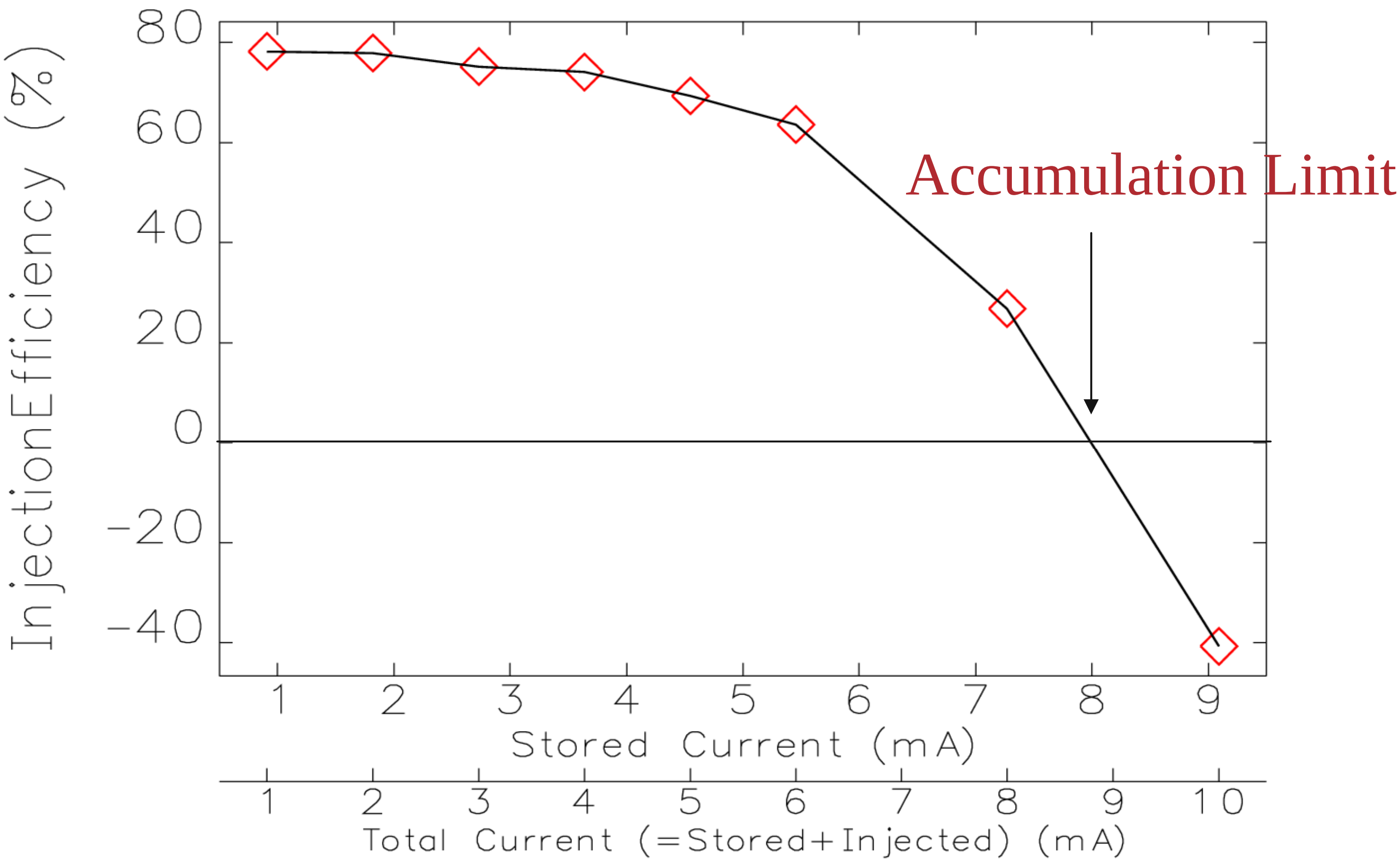
x vs. y



Coordinates of the lost particles

Slide courtesy Y.-C. Chae

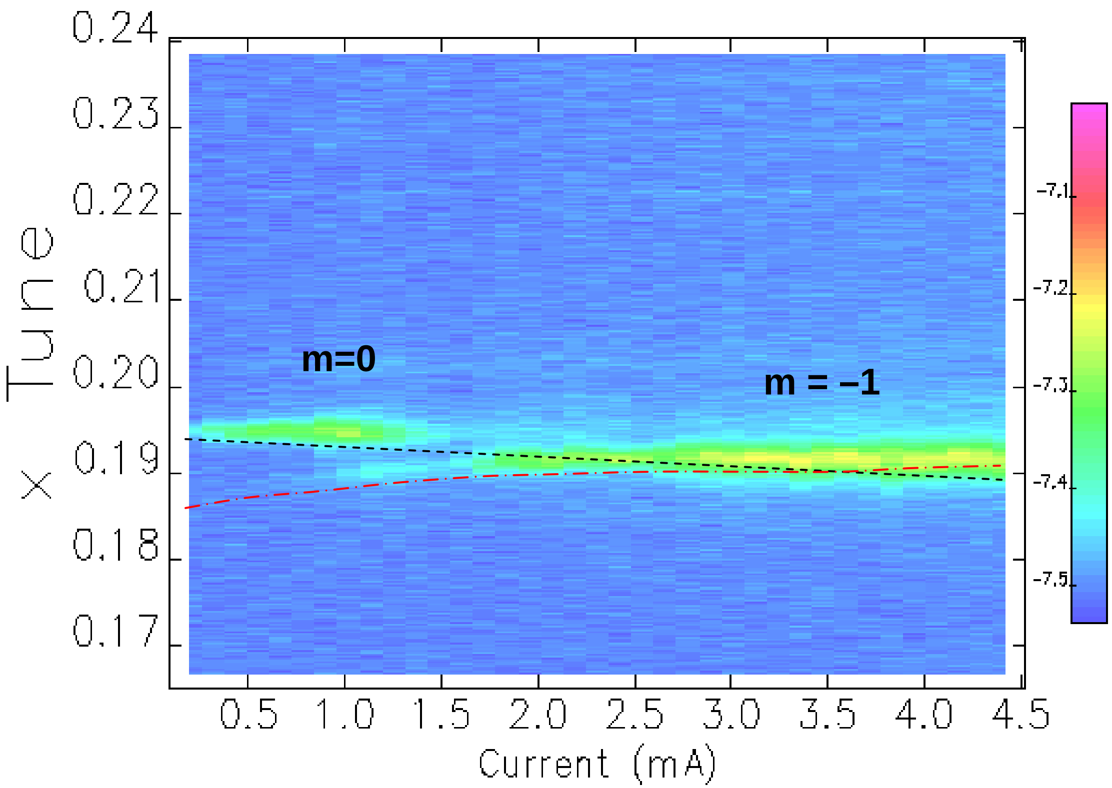
Simulated Injection Efficiency vs. Current



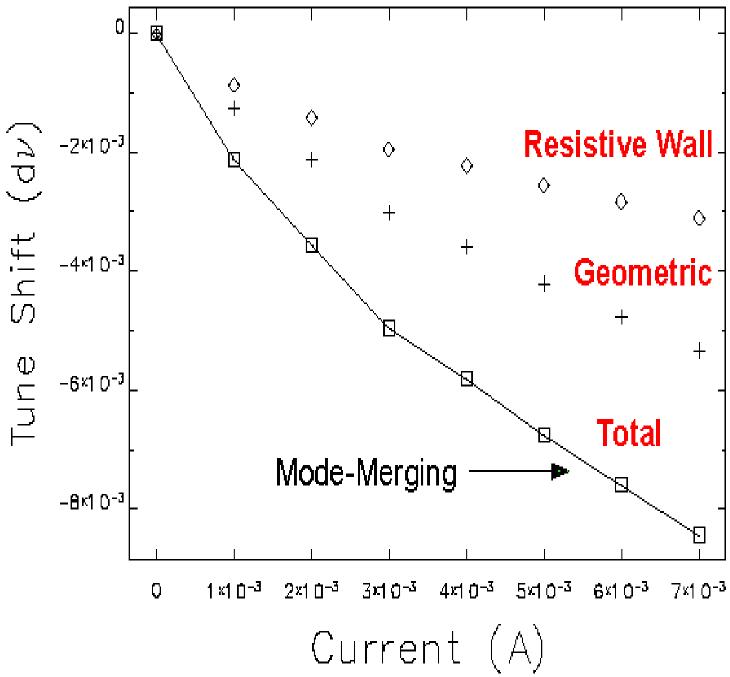
Measured Accumulation Limit < 8 mA

Slide courtesy Y.-C. Chae

Horizontal tune with current: Resistive wall larger



Measured tune slope (-0.008/mA)
[Data courtesy L. Emery]



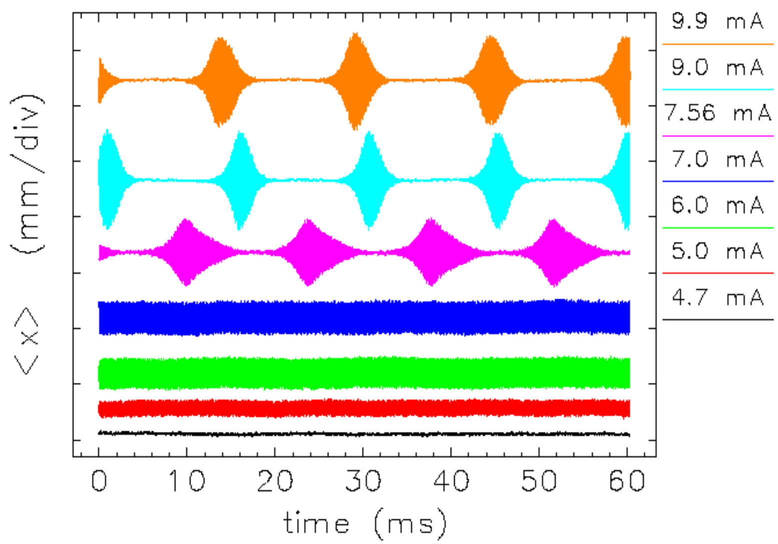
Modeled with total horizontal impedance in *elegant*[1]

[Y.-C. Chae, Proc. PAC 2003, 3011]

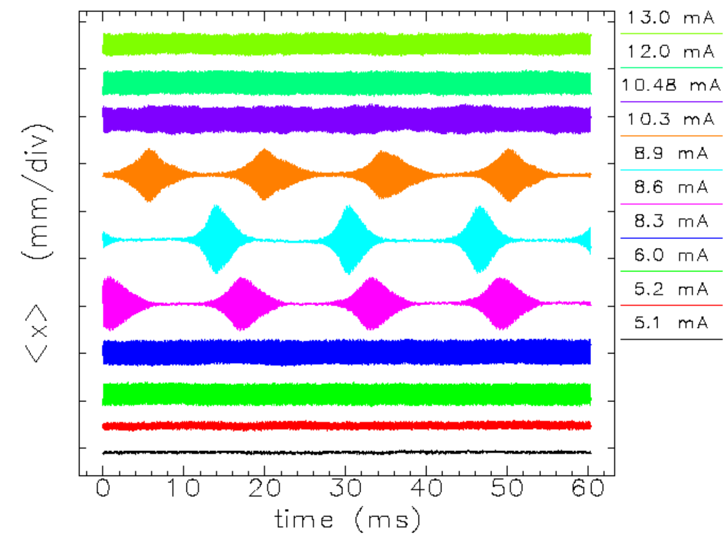
[1]M.Borland, "elegant: A flexible SDDS-compliant for accelerator simulation," APS Light Source Note 287, 2000.

Horizontal Saw-Tooth Single Bunch Instability

- Plots show beam position monitor turn-by-turn histories showing centroid motion above the instability threshold
- Chromaticity (x,y) is (3,6), 7.5 nm lattice
- Such collective transverse behavior not observed elsewhere (longitudinal only)
- Of interest is how beam size evolves, during relaxation phase in particular



Vrf=9.4 MV



Vrf=7.0 MV

K. Harkay et al., Proc. 2001 PAC, 1915

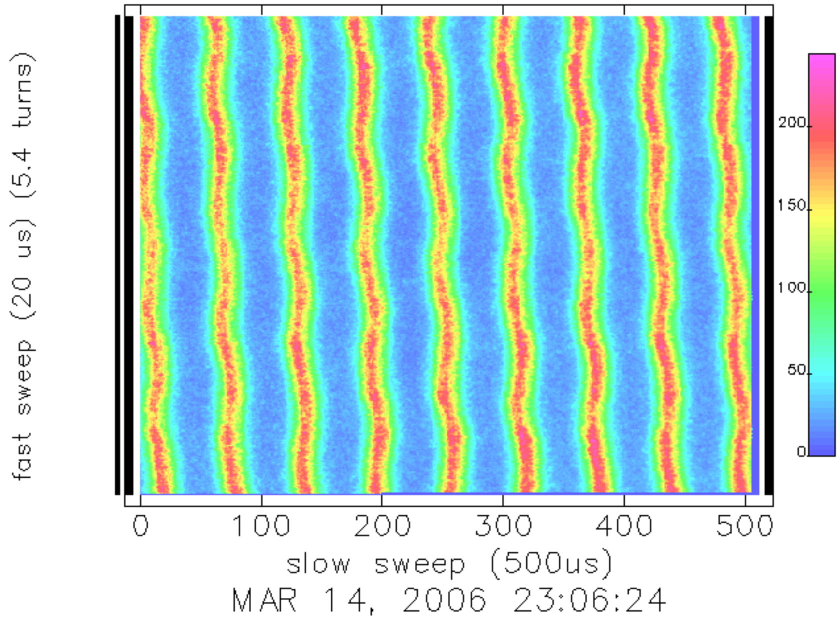
Impedance Database II

- **Impedance Database II**
  - Wake potentials of 2 mm-long or shorter bunched beams
  - 3D Electromagnetic Field Solver GdfidL (parallel program)
  - Impedance as function of frequency up to 50-100 GHz
  - Will Use to predict the collective effects in the APS storage ring
  - Applicable to ILC damping rings, etc
- **Benefit**
  - Longitudinal collective effects will be predicted correctly; this is the most important step in order to predict all other aspects of collective effects
  - 3D collective effects will be accurately predicted for injection efficiency, accumulation limit, undulator radiation damage, high current feedback system design, assessing effects of superconducting rf cavity, deflecting cavity, and assessing the effect of small gap undulator chambers
  - Powerful Linux cluster, core of this project proposal, will be available for engineers who runs 3D software for magnet, undulator, chamber, rf-device design requiring large computer memory

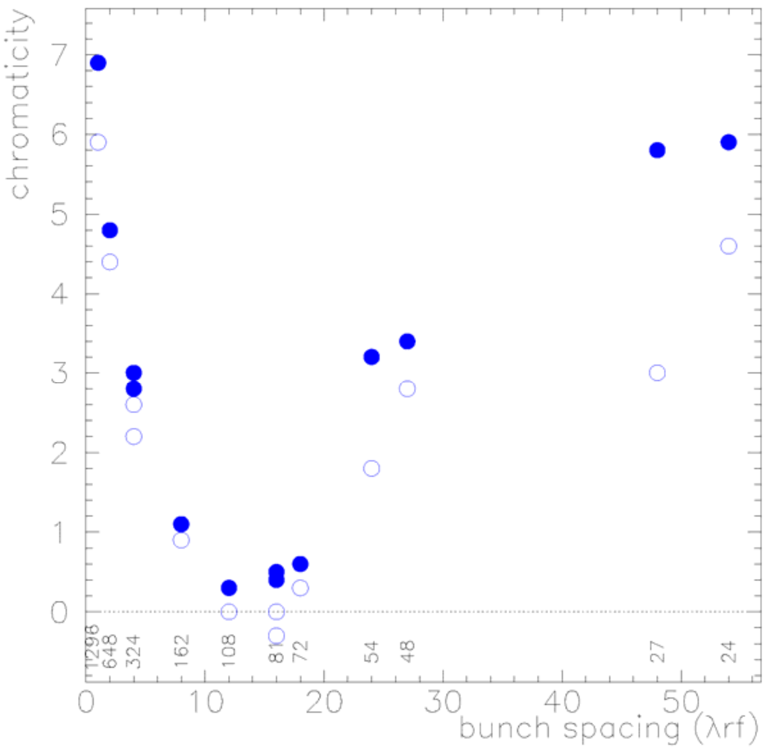
New linux cluster "Max"

- New cluster optimized for memory intensive applications: parallel 3D electromagnetic field calculations
- 16 nodes installed last week
  - 8 GB memory/node (128 GB total)
  - 64-bit memory addressing
  - 2.2 GHz interface to memory
  - 2.2 GHz processor speed
- Application: Impedance Database II – bunch structure down to 1 ps

Multibunch transverse instabilities (horizontal)



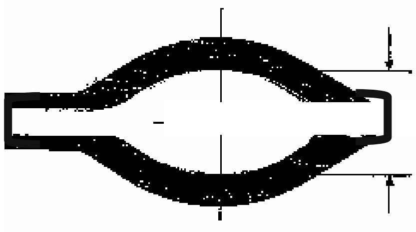
324 bunches (101.5 mA), dual-sweep streak image. Transverse coupled-bunch mode ~0.8 is clearly seen (ξ_x 1.6).



The chromaticity required to stabilize the beam shows a strong dependence on bunch spacing (100 mA total) – 12 rf bucket spacing is most stable.

Summary

- Experience benchmarking impedance calculations at APS provide guidance in designing vacuum chambers for upgrades, future rings, etc.
  - Longitudinal: transitions, interference effects
  - Vertical: transitions
  - Horizontal: vacuum chamber asymmetry



- Much progress on reproducing single bunch collective effects: multibunch to be analyzed
- Benchmarking of models, multi-particle tracking against measured data is critical to advance understanding
- Modeling effort driving towards massively parallel 3D
- More work to be done (compare APS to DR…) …

Acknowledge all my colleagues from whom I borrowed figs, slides…